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ION THRUSTER NUMERICAL MODELING

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ABSTRACT

We present further numerical results of our particle-in-cell/Monte Carlo calculations of accelerator grid erosion in an ion thruster. Comparison between numerical and experimental results suggests that the accelerator grid impingement is primarily due to ions created far downstream from the accelerator grid. In particular, for the same experimental conditions as those of Monheiser and Wilbur at Colorado State University, we find that a downstream plasma density of $2x10^{14}$ m^{-3} is required to give the same ratio of 5% of accelerator grid impingement current to beam current. For this condition, we find a potential hill in the downstream region of 2.5 V.

I. Introduction

Accelerator grid erosion is one of the remaining issues for space applications of ion propulsion. Serious accelerator grid erosion was observed in several ground lifetests on xenon ion thrusters [1,2,3]. It is thought that the accelerator grid erosion is caused by charge-exchange ions, although there has recently been some speculation that it may also be a result of ionization of the background neutral gas by electron impact. Charge-exchange ion production is proportional to the sum of the neutral density due to propellant loss from the thruster and the neutral density in the vacuum chamber. It is very important to know what role the neutral gas plays in the vacuum chamber in terms of the grid erosion in order to interpret ground test results and to predict the engine lifetime in space operation conditions. In the past two years, we have developed a PIC simulation model to simulate the ion optics and accelerator grid erosion induced by charge-exchange collisions [4,5]. However, if only those charge-exchange ions created near the accelerator region are considered, the calculated impingement current is about one order of magnitude less than the experimentally observed value.

The accelerator grid erosion rate and erosion pattern largely depend on the downstream plasma condition and the downstream electric field. It was believed and observed in the past that there was a potential hill near the accelerator grid. By assuming a certain downstream plasma density, our previous calculations did give a potential hill in the downstream region near the accelerator grid [4,5]. However, in recent experiments no significant electric potential gradient was observed in the region downstream from the accelerator grid [1,6]. Therefore, the motivation for this study is to see what downstream plasma density is required to predict the same ratio of the accelerator grid impingement current to the beam current as observed in the experiment conducted at Colorado State University [1], and to calculate the downstream electric potential field.

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The difference between these calculations and the previous ones is that ions are allowed to be extracted from the downstream plasma. By assuming a downstream plasma density, calculations for accelerator grid impingement current were made to include the contribution of ions extracted from the downstream plasma. Beyond this study, a detailed analysis of the downstream plasma effects on the accelerator grid erosion and the neutralization process are needed to simulate the downstream plasma by following both individual electrons and ions.

II. Simulation Model

Our Particle-In-Cell (PIC) and Monte Carlo simulation model for studying the ion optics and charge-exchange grid erosion is described in [4,5]. In this model, the PIC method is used to simulate the ion flow, and the Monte Carlo method is used to simulate the charge-exchange collisions.

The difference with our previous calculations is that in the present study ions can also be extracted from the downstream plasma. The reason for this is that if there are ion sources in the downstream region, ions can be extracted continuously from the plasma. The downstream plasma could result from the charge-exchange collisions between fast beam ions and neutral atoms and/or electron-neutral ionization collisions. Since, at this point, the electron density is not determined by tracking individual electron simulation particles, it is impossible to differentiate between these processes, and the calculation assumes a fixed plasma density.

Instead of tracking individual electron particles, it is assumed that the electron density n_e is in a Boltzmann equilibrium with the ion density n_0 in the downstream neutral plasma according to:

$$n_e = n_0 \exp\left[-\frac{e(\Phi-\Phi_0)}{kT}\right]$$

where e is the electron charge, k is Boltzmann's constant, T_e is the electron temperature, Φ_0 is the plasma potential, and Φ is the local potential.

III. Example Calculation

The calculations were performed for operation of the thruster on xenon propellant. The computational domain was chosen to correspond to the experimental configuration used by Monheiser and Wilbur [1]. It is assumed that a neutral plasma exists at the upstream boundary of the computational domain, with an ion temperature of 1000 *K* and an electron temperature of 1.5 *eV*. The screen grid is at a potential of 1000 *Volt* and the accelerator grid is at a potential of -500 *Volt*. The discharge voltage is assumed to be 30 *Volt*. The neutral density in the code is chosen to correspond to a vacuum chamber pressure of $7\text{x}10^{-6}$ *Torr*, and the beam current is 0.5 *mA*. Both screen and accelerator grid hole diameters are 1 cm. The separation of the two grids is 0.4 *cm*; the thicknesses of the grids are 1.5 *cm*. The center-to-center distance between two adjacent apertures is 1.5 *cm*. Calculations were performed for different downstream plasma densities, namely in the range 10^{13} to 10^{15} m^{-3}. The electron temperature of the downstream plasma was set equal to those inside the thruster, namely 1.5 *eV*.

Our two-dimensional, axisymmetric PIC/Monte Carlo code has been ported to run on a PC. Although we have shown that a three-dimensional code is necessary to calculate the pitted erosion patterns that are observed in ground tests, the two-dimensional code, which is less time-consuming, is particularly well suited to modeling the ion optics. An especially attractive feature of the new, PC-based, code is that of added graphics capability, which allows the operator to monitor continuously the flow of both the beam and charge exchange ions as the calculation is progressing. An example of this graphical output is shown in Figure 1. The upper portion of the plot shows the electric potential contours and the lower portion shows ion particles. The graphical simulation now clearly shows how these charge exchange ions (outside of the primary ion beam) proceed toward the accelerator grid.

Energy distribution of erosion ions

Figure 2 shows the energy distribution of ion particles which strike the accelerator grid. For both upstream and downstream surfaces of the accelerator grid, it can be seen that most ion particles have

energies of about 500 *eV*. This indicates that most of them are created in the downstream plasma region. In Figure 2b, those ions which have energies much less than 500 *eV* are charge-exchange ions created near the accelerator grid region. For the interior surface of the accelerator grid shown in Figure 2c, most ions have energies less than 200 *eV*. The impingement current reaching the downstream surface of the accelerator grid is more than 98% of the total accelerator grid impingement current. Therefore, it is concluded that the accelerator grid erosion is caused by those ions created far downstream from the accelerator grid inside the plasma.

Electric potential field

Electric potential contours are shown in Figure 3. In order to have a 5% ratio of the accelerator grid impingement current to the beam current, as found in Ref. 1, it was necessary to assume a downstream plasma density of about $2x10^{14}$ m^{-3}, with an assumed electron temperature of 1.5 *eV* (for these values we actually find a ratio of 4.7%). Under these conditions, the calculated downstream electric potential peak value is about 2.5 *Volt*. The plasma density of $2x10^{14}$ m^{-3} implies that the fraction of the background gas that is ionized is about 0.1 percent.

IV. Conclusion and Recommendations

Based on this study, it is confirmed that the accelerator grid erosion is caused by the ions created far downstream from the accelerator grid. To obtain about the same ratio of the accelerator grid impingement current to the beam current as observed at Colorado State University [1], we find that a downstream plasma density of about $2x10^{14}$ m^{-3} is required, with an assumed electron temperature of 1.5 *eV*.

To fully understand the role of the downstream plasma on accelerator grid erosion, several questions must be answered by the experiments: What is the downstream plasma density? What is the downstream electron temperature? How does the downstream plasma density vary as a function of the vacuum chamber pressure? And finally, does the formation of the downstream plasma result from charge-exchange collisions and/or electron-neutral ionization collisions?

From the numerical simulation side, it appears that electron particles also need to be tracked individually in order to simulate the neutralization process and provide insight into the formation of the downstream plasma.

ACKNOWLEDGMENTS

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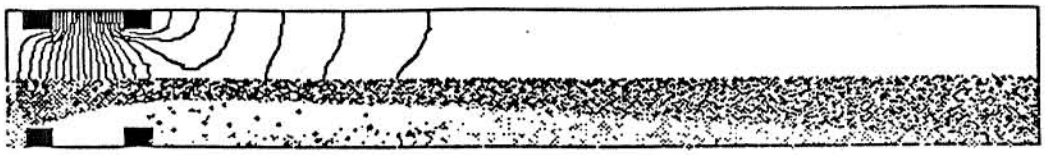

Figure 1: Typical snapshot during the simulation of the ion dynamics in the ion acceleration region of an ion thruster. Shown are electric potential contours and the positions of beam and charge-exchange ions.

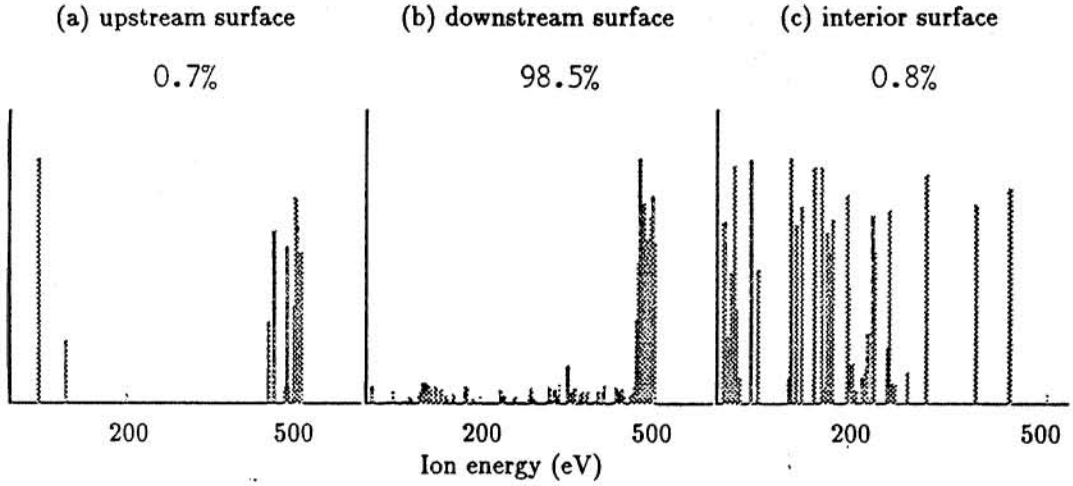

Figure 2: Energy distributions of the ions which impact the accelerator grid: (a) upstream surface, (b) downstream surface, and (c) interior surface.

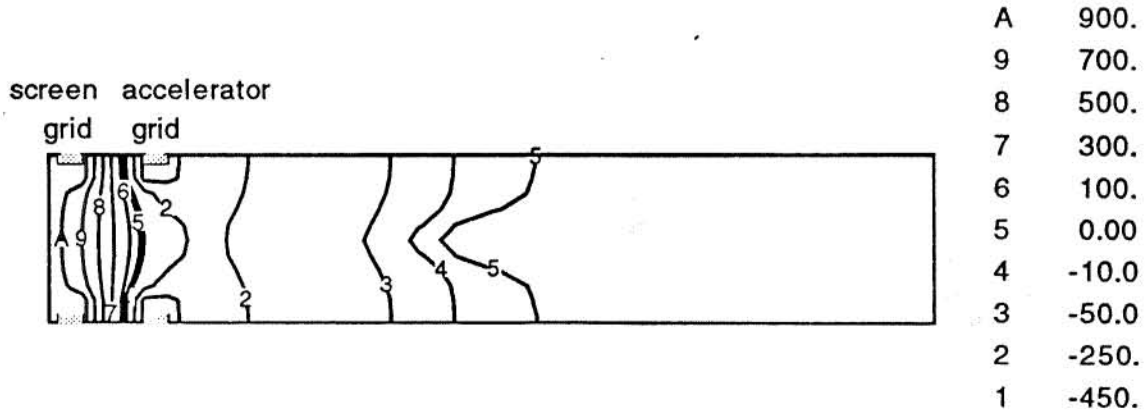

Figure 3: Electric potential contours.